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On the importance of time-synchronized operations in software-defined electronic and optical networks / GARRICH ALABARCE, Miquel; Muqaddas, ABUBAKAR SIDDIQUE; Giaccone, Paolo; Bianco, Andrea. - ELETTRONICO. - (2017). (Intervento presentato al convegno International Conference on Transparent Optical Networks (ICTON) tenutosi a Girona, Spain nel July 2017) [10.1109/ICTON.2017.8025133].

Availability:

This version is available at: 11583/2669984 since: 2018-02-28T15:47:00Z

Publisher:

IEEE

Published

DOI:10.1109/ICTON.2017.8025133

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On the importance of time-synchronized operations in software-defined electronic and optical networks

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ABSTRACT

The utilization of time-synchronized operations (TSO) is gaining interest in the research community on Software-Defined Networking (SDN). This paper discusses TSO applicability in electronic packet and optical networks. In electronic packet networks, the TSO approach has been shown to improve network performance, thanks to timed network updates. In optical networks, this approach enables novel security applications and permits to reduce lightpath disruption time. We finally discuss TSO further potentialities and requirements regarding clock availability in network elements.

Keywords: packet networks; optical networks; software-defined networking, time-synchronized operations.

1. INTRODUCTION

Carrier networks currently face operational challenges because their multi-domain, multi-technology and multi-vendor infrastructure is required to support an ever-increasing traffic volume and dynamicity [1]. Telecom operators' infrastructure commonly relies on IP over optical (wavelength division multiplexed - WDM) networks [2], which may include complex mix of services, number of layers, protocols, and eventually support new client demands or new business models. Furthermore, current carrier networks couple the control plane (which decides how to handle traffic) and the data plane (which forwards traffic according to the control plane decisions) reducing flexibility, favouring an undesirable vendor lock-in, and limiting innovation and evolution of the network infrastructure. A clear example is commercial optical network equipment, which commonly provide both data plane forwarding capabilities (i.e. lightpath routing) and control plane generalized multi-protocol label switching (GMPLS) functionalities embedded in a single product.

In this context, Software Defined Networking (SDN) enables an unprecedented level of network programmability by decoupling the forwarding data plane actions from the control plane decisions [3], thus potentially overcoming the limitations of current network infrastructure and enabling many new functionalities [4]. SDN offers a global network view that can be exploited by network applications to define routes and policies according to traffic needs, thus potentially improving network performance. This enhanced network programmability is based on standard SouthBound Interfaces (SBI) exploited by the SDN controller to directly control data plane elements. A remarkable example of SBI is based on OpenFlow protocol [5], used to update packet handling rules in the flow table which governs the switches. Indeed, OpenFlow has become the industrial standard in electronic packet networks. In optical networks, SDN provides a valuable framework to control the variety of network elements that compose the data plane in elastic optical networks (EONs) [6]. In an EON controlled using SDN, specific SBI protocol adaptations enable the control of transmission devices that support multiple baud-rates and modulation formats and of optical nodes capable to route signals with an almost arbitrary number of spectrum slots [7]. For instance, OpenFlow can be adapted to control software-defined optical network (SDON) with EON capabilities implementing the appropriate optical extensions to its standard [8].

Among the many features enabled by SDN, time-synchronized operations (TSO) are recently gaining interest in the research community. TSO define control plane instructions to be executed by the data plane elements at a specified time. In particular, TSO are implemented with the addition of timestamps to the SBI instruction messages, notably in OpenFlow [9] and NETCONF [10].

In this paper, we review recent literature on TSO and discuss its applicability. In Section 2, we survey several initiatives in electronic packet networks that employ TSO to improve network performance and enhance monitoring functionalities. In Section 3, we review TSO in optical networks that enable a novel security application and our recent proposal to reduce lightpath disruption time. We discuss TSO implementation requirements in Section 4 and summarize the paper in Section 5.

2. TIME-SYNCHRONIZED OPERATIONS IN ELECTRONIC PACKET NETWORKS

In this section, we review three initiatives that employ TSO in electronic packet networks (EPN).

2.1 TSO in EPN for flow swapping

SDN provides a global-network view to enable advanced traffic engineering policies. This may require two apparently contradictory objectives: frequent path modifications while avoiding misbehaviors (e.g. packet losses,

outages, routing loops). A conventional way to meet these objectives is to ensure spare network capacity. However, this may not be possible in case of high load conditions.

In this context, Mizrahi and Moses [11] propose and implement a TSO approach, referred to as TIME4, to efficiently manage the existing network capacity. Specifically, they target a flow swapping scenario in which no other rearrangement is possible and non-synchronous approaches may disrupt existing flows. An example based on [11] is illustrated in Fig. 1, where four un-splittable and fixed-bandwidth flows $F_{\{1..4\}}$ traverse switch A. Each link in the network has unit capacity. In case a new flow request F_5 arrives either from D or E to A, F_2 and F_4 need to be swapped to accommodate F_5 . In this example, TSO minimize the temporary congestion while not requiring extra network capacity and bandwidth modifications to the existing flows. Simultaneous and synchronous operations are required in the involved switches using time extensions that have been recently standardized in OpenFlow 1.5 by ONF [9] and in NETCONF by IETF [10].

Potential failure scenarios are discussed in [11] which include several switches failing to perform a synchronous operation or controller commands not reaching the destination switches. For these cases, the authors propose the use of TCP as reliable transport protocol for the TSO commands, or simply sending TSO messages sufficiently in advance of the execution time.

2.2 TSO in EPN for consistent network updates

Network states evolve with time and it is of paramount importance to keep consistent states between the controller(s) and the network devices, to avoid misbehaviors [12]. Two approaches are commonly used to provide network consistency in the case of state updates. On the one hand, *ordered* updates are based on sequential operations performed so that no intermediate steps generate network anomalies. This approach requires long reconfiguration times to avoid inconsistency and prevent rapid network updates. On the other hand, *two-state* updates involve packet tagging by the switches in order to identify whether packets belong to a pre-state or to a post-state update. By doing so, switches are capable to identify which set of packet matching rules need to be applied. The latter approach temporarily requires duplicate rules in the switches until no packet belonging to the pre-state update remains in the network. Thus, extra memory needs to be available in the switches' memory to hold duplicate rules.

Mizrahi *et al.* [13] address this challenge with a theoretical and experimental analysis using TSO to preserve a given level of consistency during network updates. Their implementation of TSO can be applied to improve the scalability in terms of update duration in both approaches and in terms of extra allocated memory only in the two-state update case. Consequently, a trade-off arises between the desired level of consistency and the achieved scalability. In both approaches, TSO can be scheduled closer in time but at the cost of brief inconsistency periods. For the two-state approach, limiting the memory resources for the flow table could improve scalability, but increase the inconsistency period.

2.3 TSO in EPN for accurate bandwidth monitoring

Megyesi *et al.* [14] propose the usage of TSO in an SDN-enabled network to improve the measurement of the available bandwidth (ABW). ABW is defined as a dynamic metric to account for the instantaneous amount of traffic that can be added to a path without disrupting other flows. An updated knowledge of the ABW can be exploited by the network operator for agile traffic engineering applications, like highly dynamic routing, traffic consolidation and adaptive video.

Traditional techniques to measure ABW follow two approaches. Active techniques involve pro-actively sending probe packets in the network causing temporary congestion to infer the ABW. Passive techniques may use multiple measurement points in the network and require synchronization of the measurements, thus are rarely used. Authors point out that these techniques are scenario dependent, have limited accuracy and long convergence times.

The major contribution in [14] is an SDN-based ABW measurement application that exploits the global view of the network. An analytical model and an experimental evaluation are reported to address the inaccuracy of the ABW measurements when using the aforementioned application. Inaccuracy occurs because switches are polled by the SDN controller asynchronously and without information regarding the precise sampling time. Subsequently, the authors claim that inaccuracy can be avoided if adopting TSO, and they propose an ad-hoc extension of the OpenFlow header to support TSO. In particular, the counter values in the flow tables of the switches are reported to the controller with the corresponding timestamp.

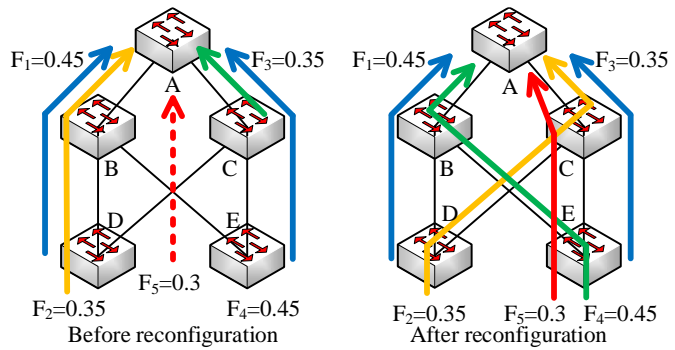


Fig. 1: Flow swapping example

3. TIME SYNCHRONIZED OPERATIONS IN OPTICAL NETWORKS

In this section we review two recent approaches that exploit TSO in optical networks

3.1 TSO in optical networks for security

Li *et al.* [15] propose a novel SDN-based security application for optical networks, referred to as fast lightpath hopping (LPH), to prevent eavesdropping and jamming. LPH combines a set of multiple precomputed lightpaths by the SDN controller and TSO among multiple optical nodes. In particular, multi-lightpath computation is performed solving an Integer Linear Programming (ILP) problem, which considers both wavelength and timeslot allocation and minimizes the total number of shared physical links among the lightpaths. Subsequently, the data flow hops among these multiple lightpaths in a sequential manner, as dictated by the SDN controller. TSO, implemented as modifications in the OpenFlow header, enable the synchronization between the involved optical nodes in the LPH procedure. Authors experimentally demonstrate the LPH application in a 4 node testbed, achieving a hop frequency of 1 MHz with acceptable bit error rate.

3.2 TSO in elastic optical networks to reduce disruption time for lightpath swapping

EON enables an efficient use of spectrum resources combining dynamic routing and spectrum assignment (RSA) schemes with defragmentation techniques [16]. However, highly loaded scenarios may generate “end-of-line situations”, defined by [16] as cases in which the defragmentation is not able to consolidate scattered frequency slots (FS) in the network.

In this context, we recently proposed in [17] the usage of TSO in EONs to minimize disruption time during lightpath reassignment. The proposal is motivated with an end-of-line situation due to non-continuous vacant FS illustrated Fig. 2. The presence of 4 lightpaths (numbers in the spectrum indicate their number of FS) leave only 1 slot available in both $A-B-D$ and $A-C-D$ paths. A new lightpath request (L_5) of 2 FS from A to D can only be accommodated if lightpaths are swapped, as shown in Fig. 3. A conventional approach, denoted as ASY, would execute four operations asynchronously. In particular, L_1 is first disrupted, L_3 is rerouted in two operations and finally L_1 is restored in the new path.

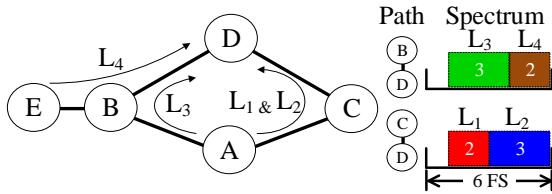


Fig. 2: Topology with lightpaths in an end-of-line scenario

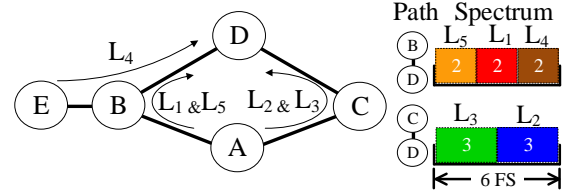


Fig. 3: Re-routing to accommodate a new lightpath

The lightpath disruption time for L_1 can be reduced if TSO are combined with bundles of commands so that all nodes operate simultaneously at the scheduled time. This combination is compatible with OpenFlow 1.5 [9]. In [17], we analytically compare the performance of the ASY against the TSO approach in a general scenario which includes source, intermediate and destination nodes (e.g., source: A , intermediate: B and C , destination: D in Fig. 2). We report a 75% of disruption time reduction in the test scenario mainly due to one single operation, thanks to TSO, instead of 4 sequential operations in the conventional ASY approach.

4. DISCUSSION OF TSO IN SDN

As noticed in the previous sections, TSO enable a number of novel applications and permit the enhancement of network performance. However, it is important to emphasize that TSO should be considered as a tool which needs to be jointly used with existing techniques to improve performance, to better address existing challenges or to develop new applications. For instance, in EON a challenging scenario occurs when a set of lightpaths present spectrum inter-dependency, preventing parallel defragmentation [18]. Thus, to achieve defragmentation this dependency needs to be broken following a sequence of lightpath rearrangements, which leads to disruption. In this case, TSO can be employed to improve the sequential defragmentation by reducing the disruption time, as discussed in Section 3.2.

Regarding TSO implementation, all the applications assume that the SDN controller and the data plane elements have access to a common time reference that enables synchronization. A possible implementation choice is IEEE PTP standard [19], commonly available in packet networks, which enables precise synchronization of clocks. Moreover, an improved version of PTP for SDN networks, named ReversePTP [20], can be used in which the SDN controller keeps track of the clock offsets for each data plane element. Alternatively GPS can also be used as backup for the reference clock.

5. SUMMARY

Time-synchronized operations (TSO) are in a nascent stage within the paradigm of SDN. Despite this, there is a growing interest in the research community to exploit TSO in electronic packet as well as optical networks. In this paper, we reviewed recent literature on TSO and discussed its applicability. Regarding electronic packet networks, we highlighted how TSO can improve network performance by efficiently using the available capacity and by managing consistency during network updates. Moreover, TSO can improve the precision of bandwidth monitoring in OpenFlow-based switches. For optical networks, TSO enable lightpath hopping among different routes relevant for a novel security application. Finally, we reviewed our recent proposal that exploits TSO and bundling operations to achieve disruption time reduction during spectrum reallocation.

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